Electric Power Systems Research 108 (2014) 331–339

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

# Modal parameters identification of power transformer winding based on improved Empirical Mode Decomposition method

Chao Geng, Fenghua Wang*, Jun Zhang, Zhijian Jin

*Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China*

ARTICLE INFO

*Article history:*
Received 15 July 2013
Received in revised form 5 December 2013
Accepted 7 December 2013
Available online 28 December 2013

*Keywords:*
Empirical Mode Decomposition
Masking signal
Modal parameter identification
Power transformer
Winding

ABSTRACT

Modal parameters of power transformer winding are closely related to transformer manufacturing and detection technology of winding deformation based on vibration analysis method. Aimed at identifying the modal parameters of transformer winding accurately, a modal experiment is designed and made on a real 10 kV power transformer. An improved Empirical Mode Decomposition (EMD) algorithm is proposed to identify the modal parameters of transformer winding with obtained experiment data. First, Ensemble Empirical Mode Decomposition (EEMD) is applied to decompose the vibration signals roughly. Then a masking signal is introduced to eliminate the mode mixing effect with the selected masking frequency. Finally, EMD is used again to get the final Intrinsic Mode Functions (IMFs). By applying the Hilbert transform to the obtained IMFs, modal parameters of power transformer winding are calculated. The PolyMax method is also used to extract modal parameters of transformer winding as a comparison. Calculated results have shown that natural frequency obtained by two methods matches well and the proposed method shows better accuracy in the identification of damping ratio, which verifies the effectiveness of proposed method to recognize the modal parameters of transformer winding with high accuracy.


## 1. Introduction

As one of the most important equipment for the transmission and distribution of power system, failures of power transformer will cause disturbance in power grid and may give rise to huge losses [1]. Statistics have shown that the rate of transformer failure aroused by winding deformation remains high in the past several years. Excited by the great electromagnetic force resulting from the interaction between winding current and leakage magnetic, transformer winding vibrates in both axial and radial direction with the possible occurrence of winding loosen. If the natural frequency of transformer winding is close to the excitation frequency, known as 100 Hz, resonance will be produced with great increment in vibration amplitude, which may lead to severe winding deformation and damage of winding insulation [2,3]. Meanwhile, with the application of many new materials and new structure design to the power transformer for the reduction of manufacture cost, mechanical characters of transformer winding are varied consequently [4]. So it is necessary for transformer manufacturers to obtain the detailed information of the mechanical parameters of transformer winding to ensure sufficient mechanical strength to endure the impact of short-circuit, since mechanical stability is always the essential considerations in transformer designing [5].

In addition, as power transformers are always subjected to many external impacts in the grid, more attentions have been paid by the power grid company to the application of various condition monitoring technologies, including thermography of winding and partial discharge detection, for the reliable power supply [6,7]. Due to the high sensitivity to variations of winding mechanical condition, winding condition detection technology based on vibration signals is becoming a hotspot with many interesting results [1,2]. Modal parameter, as the direct reflection to the mechanical character of transformer winding, can provide theoretical reference for such kind of detection technology by investigating the alterations of those parameters under different operation conditions. Therefore, it is of great importance to identify the modal parameters of transformer winding with high accuracy for both the manufacturer and operation staff in power grid.

Currently, several works have been done towards the exploration of inherent mechanical characters of transformer winding. The common mass-spring system model for the axial vibration of power transformer winding was applied to obtain the axial vibration characteristics of winding under steady condition and sudden short-circuit fault [8,9]. The relations between compression force and natural frequency were analyzed. Meanwhile, the finite element method (FEM) was applied to model the transformer winding in [9] to calculate the vibration displacements excited by the short-circuit electro-dynamic forces. It was seen that the natural frequency of the active part was increased with the increase of pre-compression. Modal analysis and experiment

* Corresponding author.
*E-mail address:* fhwang7723@sjtu.edu.cn (F. Wang).

0378-7796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2013.12.002

investigation were made on the on-load vibration of model windings in [3]. The relation between pre-compression force and first-order natural frequency was also discussed. On-load vibration of transformer winding was investigated on a model coil experimentally in [10]. The steady state response of transformer winding was estimated simultaneously with the FEM model of the winding. However, most researches are focused on the calculation of mathematical model of transformer winding with the limited modal experiments conducted on small winding models instead of real transformer winding, from which only the first natural frequency is identified. But due to the complex mechanical structure of transformer winding, the simulation model cannot always reflect the precise mechanical character of a real winding. Moreover, when the winding conditions are changed, all the inherent mechanical characters are varied consequently. The high frequency components in the monitored vibration signals are newly appeared and increased apparently. Hence, it is not enough to take into account the first natural frequency merely. In addition, the existed modal parameter identification methods can be divided into time domain methods and frequency domain methods, such as Ibraham's Time Domain (ITD) [11], Stochastic Subspace Identification (SSI) [12] and PolyMax [13], which are widely used in some given mechanical structure for the modal parameter identification. The vibration signals, measured in the transformer winding are always nonlinear and non-stationary mixed with noise due to its complex mechanical structure, which is difficult for the conventional methods to obtain the modal parameters accurately and need to make further research.

In this paper, a modal experiment is designed and made on a 10 kV transformer winding and the experiment procedure is listed in detail. An improved Empirical Mode Decomposition (EMD), which is appropriate for the analysis of nonlinear and non-stationary signal, is presented to identify the modal parameters of transformer winding. In order to illustrate the effectiveness of the proposed method, PolyMax method is used to obtain the modal parameter as a comparison. The influences of masking signal frequency and sampling frequency to the identification results of the proposed method are also investigated.

## 2. Theoretical foundations

### 2.1. Modal response of multi-degree of freedom system

Transformer winding is generally considered as a typical multi-degree of freedom system and its vibration response is a combination of several modal responses, which could be expressed as in the following form.

$$\mathrm{M}\ddot{x}(t) + \mathrm{C}\dot{x}(t) + \mathrm{K}x(t) = F(t) \quad (1)$$

where M is mass matrix, K is stiffness matrix, C is damping matrix, $x(t)$ is coil displacement, and $F(t)$ is exciting force.

According to the modal superposition theory [14], vibration response of an arbitrary point on a given mechanical structure under impulse excitation is

$$x_\mathrm{r}(t) = \sum_{r=1}^{n} A_\mathrm{r} e^{-\varsigma_\mathrm{r}\omega_\mathrm{r} t} \cos(\omega_{\mathrm{dr}} t + \phi_\mathrm{r}) \quad (2)$$

where $\varsigma_\mathrm{r}$ is damping ratio, $\omega_\mathrm{r}$ is natural frequency, $\omega_{\mathrm{dr}}$ is damped natural frequency, $A_\mathrm{r}$ is coil response amplitude, $\phi_\mathrm{r}$ is initial phase of the winding structure.

It is seen that the impulse response of transformer winding is a multi-component signal with different frequency components. If the frequency components, which represent for one modal response each, can be decomposed and extracted from the original impulse response, then the Hilbert transform can be applied to identify the modal parameters.

### 2.2. Modal parameter identification based on improved EMD

EMD is an effective method to decompose the nonlinear, multi-component signals, which was first introduced by Huang [15]. For an arbitrary signal $x(t)$, the basic steps of EMD are as follows.

(1) *Sifting process*: Define the local extremes of $x(t)$, and connect all the local maxima and local minima with cubic spline curve known as the upper envelope and the lower envelop, respectively. Note that the upper envelop and the lower envelop should encompass all the data. Compute the mean of the two envelops and subtract it from the original signal. The difference between the original signal and the mean is the first component, designated as $h_1(t)$.
(2) *Check process*: Check whether the first component $h_1(t)$ is an Intrinsic Mode Function (IMF) or not, which should satisfy the following two requirements.

(a) The number of zero crossings and extremes must either equal or differ at most by one in the whole data set.
(b) At any point, the mean value of the two envelops equals zero.

If $h_1(t)$ does not satisfy the two requirements, let $x(t) = h_1(t)$ and repeat the sifting process. Otherwise, define $c_1(t) = h_1(t)$ as the first IMF of the original signal.

(3) *Loop process:* Define $r_1(t) = x(t) - h_1(t)$ as the new signal to be decomposed. Repeat the calculation process stated above and get the second IMF, designated as $c_2(t)$. Stop the entire calculation until the residue $r_n(t)$ is smaller than a predetermined value or the residue $r_n(t)$ is a monotonic function from which no more IMF can be extracted.

However, one IMF always contains more than one frequency signal component due to the inherent mode mixing effect of the conventional EMD in practical application, which would bring about severe negative effects on the accuracy of modal parameter identification. Of all the existed methods to eliminate the mode mixing effect, Ensemble Empirical Mode Decomposition (EEMD) [16] and Band Restricted Empirical Mode Decomposition (BREMD) [17] have shown good decomposition feature in many practical applications. In EEMD, white noise is added to the original signal before EMD procedure, while masking signal is used to modify the bandwidth of the IMFs in BREMD. Since the white noise signal could project the bandwidth of the IMFs into a uniform frequency frame, and the masking signal could adjust the bandwidth adaptively according to different original signal, the combination of EEMD and BREMD method is proposed here and applied to obtain the modal parameters of transformer winding for better results. The improved EMD method can be described as follows.

(1) For an arbitrary signal $x(t)$, decompose the original signal to obtain the first IMF by EEMD method, designated as IMF1.
(2) Apply the Hilbert transform to the obtained IMF1, the instantaneous frequency and instantaneous amplitude of IMF1 can be obtained. Then the frequency of the masking signal can be calculated.

$$f = M\frac{\sum_{i=1}^{k} a_1(i) f_1^2(i)}{\sum_{i=1}^{k} a_1(i) f_1(i)} \quad (3)$$